Final Report for AOARD Grant FA23861014021 – MAGIC 2010 RASR Team

December 15, 2010

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Period of Performance: 19 Nov 2009 to 11 Jan 2011

Ref: CONTRACT NO: FA2386-10-1-4021 (MOD P00002)
Basic Research Grant: AOARD 104021 MAGIC 2010 Competition - Robotic Research Team (RASR)

Abstract: The RASR team developed a system for the coordination of groups of unmanned ground vehicles (UGVs) that can execute a variety of military relevant missions in dynamic urban environments. Historically, UGV operations have been primarily performed via tele-operation, requiring at least one dedicated operator per robot, and requiring substantial real-time bandwidth to accomplish those missions. Our team goal was to develop a system that can provide long term value to the war-fighter, utilizing MAGIC 2010 as a stepping stone. To that end, we self-imposed a set of constraints that would force us to develop technology that could readily be used by the military in the near term: (1) Use a relevant (deployed) platform, (2)Use low-cost, reliable sensors, (3) Develop an expandable and modular control system with innovative software algorithms to minimize the computing footprint required, (4) Minimize required communications bandwidth and handle communication losses and, (5) Minimize additional power requirements to maximize battery life and mission duration

Introduction: Small unmanned ground vehicles (UGVs) save lives in Iraq and Afghanistan by distancing humans from dangerous areas. These robots are instrumental in EOD applications, including improvised explosive device (IED) detection and neutralization. However, current controllers require at least one operator for each robot. An operator must tele-operates a single UGV to the suspect object where the operator remotely manipulates and deactivates the IED. All of these operations are performed using remote video requiring the complete attention of the operator.

Experiment: To help break the 1:1 ratio needed for unmanned vehicles operation and to promote autonomous control of small Unmanned Ground Vehicles, the Defence Science & Technology Organisation (DSTO) in Australia and the Research Development & Engineering Command (RDECOM) in USA took the lead in organizing MAGIC 2010. This challenge requires multi-vehicle robotic teams that can execute an intelligence, surveillance and reconnaissance mission in a dynamic urban environment. To complete the challenge, competitors must: (i) accurately and completely explore and map the challenge area; (ii) correctly locate, classify and recognize all simulated threats; and (iii)

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE **16 DEC 2010**	2. REPORT TYPE **Final**	3. DATES COVERED **19-11-2009 to 11-01-2011**

4. TITLE AND SUBTITLE **MAGIC 2010 The Robotic Research Team**	5a. CONTRACT NUMBER **FA23861014021**
	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S) **Alberto Lacaze**	5d. PROJECT NUMBER
	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES) **Robotic Research, LLC,Quince Orchard Road,Suite 300,Gaithersburg, ,MD,20878**	8. PERFORMING ORGANIZATION REPORT NUMBER **N/A**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES) **AOARD, UNIT 45002, APO, AP, 96338-5002**	10. SPONSOR/MONITOR'S ACRONYM(S) **AOARD**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S) **AOARD-104021**

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT
The RASR team developed a system for the coordination of groups of unmanned ground vehicles (UGVs) that can execute a variety of military relevant missions in dynamic urban environments. Historically, UGV operations have been primarily performed via teleoperation, requiring at least one dedicated operator per robot, and requiring substantial real-time bandwidth to accomplish those missions. Our team goal was to develop a system that can provide long term value to the war-fighter, utilizing MAGIC 2010 as a stepping stone. To that end, we self-imposed a set of constraints that would force us to develop technology that could readily be used by the military in the near term: (1) Use a relevant (deployed) platform, (2)Use low-cost, reliable sensors, (3) Develop an expandable and modular control system with innovative software algorithms to minimize the computing footprint required, (4) Minimize required communications bandwidth and handle communication losses and, (5) Minimize additional power requirements to maximize battery life and mission duration. The RASR Team (Reconnaissance and Autonomy for Small Robots) was selected to be among the 6 finalists for MAGIC 2010. The RASR Team placed third in the final competition. The technology developed by Robotic Research will be further advanced in order to be transitioned to small unmanned ground vehicles for US military.

15. SUBJECT TERMS
Robotics, UGV, Unmanned ground vehicle, autonomy, artificial intelligence, multi-agent cooperation

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT **unclassified**	b. ABSTRACT **unclassified**	c. THIS PAGE **unclassified**	**Same as Report (SAR)**	**15**	

Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std Z39-18

complete all phases within 3.5 hours.
The challenge event was conducted in Australia during November 2010.

The challenge is mindful that, at the current state of autonomy, operators will still provide oversight of the UGVs. Therefore, this challenge also forces developers to design a Human Machine Interface (HMI) that minimizes operator workload and increase overall effectiveness.

The RASR team believes that the challenge is a realistic step toward the next generation of small UGV operation and that our solution introduces a new philosophy of distributed control that is well suited for the platform size and reduced communication bandwidth.

Results and Discussion: The RASR Team (Reconnaissance and Autonomy for Small Robots) was selected to be among the 6 finalists for MAGIC 2010. The RASR Team placed third in the final competition. The technology developed by Robotic Research will be further advanced in order to be transitioned to small unmanned ground vehicles for US military.

List of Publications:
Lacaze, A., Murphy, K. (Robotic Research, LLC) and Del Giorno, M (Del Services, LLC); Reconnaissance and Autonomy for Small Robots (RASR): MAGIC 2010 Challenge, Land Warfare Conference, Brisbane, Australia, (2010)

There are no patents being pursued at this time.

DD882: Attached.
Detailed documentation: listed below is the detailed report as presented at the Land Warfare Conference, Brisbane; November, 2010

The Reconnaissance and Autonomy for Small Robots (RASR): MAGIC 2010 Challenge

Alberto Lacaze and Karl Murphy, Robotic Research, LLC
Mark Del Giorno, Del Services, LLC

ABSTRACT

The RASR team developed a system for the coordination of groups of unmanned ground vehicles (UGVs) that can execute a variety of military relevant missions in dynamic urban environments. Historically, UGV operations have been primarily performed via tele-operation, requiring at least one dedicated operator per robot, and requiring substantial real-time bandwidth to accomplish those missions. Our team goal was to develop a system that can provide long term value to the war-fighter, utilizing MAGIC 2010 as a stepping stone. To that end, we self-imposed a set of constraints that would force us to develop technology that could readily be used by the military in the near term:

- Use a relevant (deployed) platform
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- Develop an expandable and modular control system with innovative software algorithms to minimize the computing footprint required
- Minimize required communications bandwidth and handle communication losses
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1. Introduction

Small unmanned ground vehicles (UGVs) save lives in Iraq and Afghanistan by distancing humans from dangerous areas. These robots are instrumental in EOD applications, including improvised explosive device (IED) detection and neutralization. However, current controllers require at least one operator for each robot. An operator must tele-operates a single UGV to the suspect object where the operator remotely manipulates and deactivates the IED. All of these operations are performed using remote video requiring the complete attention of the operator.

To help break this 1:1 ratio and to promote autonomous control of small Unmanned Ground Vehicles, the Defence Science & Technology Organisation (DSTO) in Australia and the Research Development & Engineering Command (RDECOM) in USA took the lead in organizing MAGIC 2010. This challenge requires multi-vehicle robotic teams that can execute an intelligence, surveillance and reconnaissance mission in a dynamic urban environment. To complete the challenge competitors must: (i) accurately and completely explore and map the challenge area; (ii) correctly locate, classify and recognize all simulated threats; and (iii) complete all phases within 3.5 hours. The challenge event will be conducted in Australia during November 2010.

The challenge is mindful that, at the current state of autonomy, operators will still provide oversight of the UGVs. Therefore, this challenge also forces developers to design a Human Machine Interface (HMI) that minimizes operator workload and increase overall effectiveness.

The RASR team believes that the challenge is a realistic step toward the next generation of small UGV operation and that our solution introduces a new philosophy of distributed control that is well suited for the platform size and reduced communication bandwidth. See Figure 1.

Figure 1 Eight RASR-Bots at the beginning of a training run.

1.1 Design Philosophy

Our long term goal, resulting from our competing in Magic 2010, is to develop relevant technology for control and coordination of multiple small UGVs. Our choices of platform, sensing, and computational engine had to provide a clear pathway to deployment. Decisions taken throughout the design process have been guided to provide a low cost autonomous mission module that is deployable. Cost was a large parameter in our sensor, localization and radio selections. We could have "bought our way out of the problem" in many circumstances by purchasing more LADAR sensors, a higher quality navigation components, or advanced computing hardware, but those decisions would have yielded a system that would be prohibitively expensive for broad acceptance.

1.1.1 Risk reduction

Our overall approach was based on an up-front risk reduction process. That process flowed to both software and hardware requirements during the initial design phase. High-risk elements were identified and considered as key factors when performing trade studies and choosing among various approaches to solving the MAGIC problem.

Hardware risks were often mitigated using as much proven COTS sensors and components as possible. When custom hardware designs were required, they were fabricated early in the process to allow time for the "gotchas" that often follow with custom hardware. As an example: our custom navigation electronics solution running on the Talon platform is currently at revision level 8. Some revisions were based on required redesign efforts, and others were based on additional requirements discovered as the design process evolved. By identifying that component as a high-risk element early in the process and tackling the design early, each of those intermediate iterations were much lower risk, making for a better product in the end.

Software risks were also addressed by working on the hard problems first. By the time of our site visit, we had already coded and tested substantial portions of the identified high-risk elements (coordination planners, real-time control & navigation of a tracked system, operations in comms-denied environments), while lower-risk items were delayed since they didn't have as much potential of changing the overall system architecture.

1.1.2 A Relevant Platform

The Intelligent Systems Division at NIST tests small robotic platforms utilizing a calibrated ASTM qualified course. Vehicles that are currently in theatre or are being considered for deployment are tested in this “do or die” test. Tested vehicles in the MAGIC weight category include: The Dragon Runner, Souryu IV, G2bot, Element, UMRS 2009, Kenaf, Quince, Matilda 1, Matilda 2, Packbot 510, Mutech-R4, Helios, KOHGA, Talon, TeleMax, Caliber MK3, Andros HD-1J and Andros Mini.

These vehicles have one common denominator: they are all tracked. The DoD understands that wheeled vehicles in this weight class are simply not relevant for current operations. It was our decision from the beginning of the program to utilize a tracked vehicle even though wheeled vehicles would simplify the navigation and mapping aspects of this competition. We selected QinetiQ-NA’s (QNA) Talon platform, however, we want to emphasize that the resulting solution can be adjusted/adapted to smaller platforms, like the Dragon Runner. See Figure 2.

1.1.3 Sensing

Sensors are often the culprits of cost escalation for autonomous systems. To keep the cost down, we utilized a single COTS LADAR sensor. Utilizing multiple LADARs would have made the problem simpler, and reduced the software requirements at the cost of reducing the deployability of the system. We chose to take the harder path and make up for it in software. Although this approach added risk, these risks were identified and mitigated early-on in our design process for an overall reduction in our risk assessment process.

1.1.4 Navigation System

IMUs are another example of where we could have “bought our way out of the problem.”

In urban warfare, it is common to encounter GPS denied and multipath situations where GPS (even subscription versions) is not sufficient to provide the localization accuracy needed to accurately map the scenario.

There are a variety of COTS navigation solutions in the US $50-100k range that would provide inertial backing to support the accuracy requirements. It is our opinion, that the overall cost of an autonomous system that has a component in this cost range would not be appealing for military or other applications. Therefore, we developed for MAGIC a navigation unit in the US $10k range and tailored it to the mission constraints.

1.1.5 Data Radios

In current teleoperated systems, where a constant communication links is required, the DoD customers usually opt for radios that are not at the top of the price range. This is evident by the radio selection in the Talon systems and in iRobot’s Packbot, arguably the most popular platforms currently in theater. Therefore, we opted for radios in the same price range, concentrating instead on the autonomy and software smarts to deal with comms losses which are bound to happen -- no matter how expensive the radio..

1.1.6 Computing platform

The MAGIC competition requires advanced multi-asset coordination and planning systems in order to accomplish the mission. There is a great temptation to “throw computers at the problem.” Our MAGIC team resisted, opting

Figure 2 Eight RASR-Bots map the interior of a large building

for designing algorithms that execute within a high-efficiency software architecture framework.

We selected a single commercial computing platform, a Mac Mini. Although not rugged for field deployment, several ruggedized platforms have similar computational power. We implemented a mixture of real-time control algorithms with high- and mid-level planners that work as a unit to use as little computing power as needed. In addition to lower cost and complexity another advantage of minimizing computing hardware is to lessen the burden on the battery system, allowing for missions of up to 4 hours without recharging the Talon.

1.1.7 Relevant autonomous mobility and coordination software

Since much of our design criteria heavily weights the overall cost and deployability of the team, the autonomous mobility system must be robust enough to cope with this decision. In particular it must be able to cope with the treaded platform, the midrange sensors

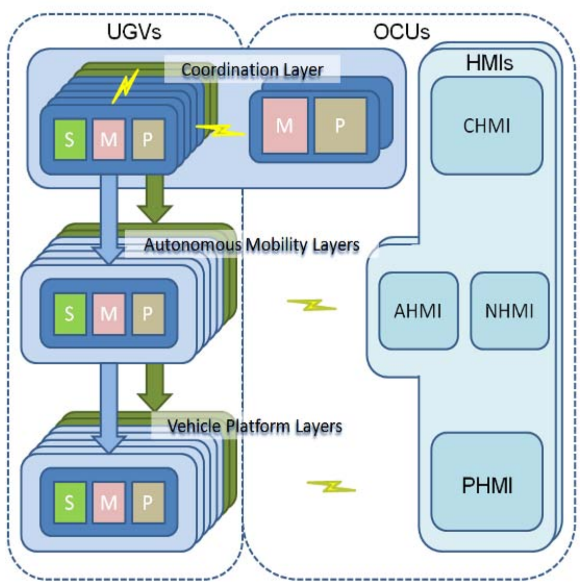

Figure 3 The overall system provides autonomous mobility coordination and communications loss resiliency

capabilities and inexpensive IMU components. Moreover, the vehicle cooperation infrastructure must provide intelligent behavior while the vehicle is out of comms. We spent a significant portion of our budget and time designing and implementing software for the hard constrains that the MAGIC 2010 imposed on us as well as our own constraints from what our team partners at GDRS and QNA have experienced from deployed systems.

1.2 Overall system description

Hardware and software solutions are summarized in this section and are explained in detail in the following sections.

1.2.1 Hardware

The RASR Team is composed of eight platforms (6 sensor UGVs and 2 disruptor UGVs), and 2 Operator Control Units (OCUs). Each robot has a sensor pod providing 360 by 90 degree LADAR coverage, 360 by 90 degree camera coverage, an INU, two data radios (data and E-STOP), and a main computer.

1.2.2 Systems architecture

The systems architecture is composed of a distributed/hierarchical control architecture and a matching Human Machine Interface. See Figure 3. The control architecture is composed of the Coordination Layer, the Autonomous Mobility Layer and the Vehicle Platform Layer. Each layer in the control hierarchy contains Sensing,

Modeling and Planning (S,M,P) modules. The Coordination Layer maintains the overall situational awareness and exposure measures. This layer is distributed among the robots and the base station. At the OCU, a corresponding Coordination Human Machine Interface (CHMI) provides the operators with coordination oversight. The Autonomous Mobility Layer performs local path planning and OOI neutralization. A separate copy resides on each robot At the OCU, a corresponding Autonomy HMI (AHMI) and a Neutralization HMI (NHMI) assign coarse scheduling tasks to provide oversight for these operations. The Vehicle Platform Layer provides low level control functions including path following, communication infrastructure and e-stop functions. At the OCU, the Platform HMI (PHMI) provides the operator with oversight of platform issues. The different functionalities of the HMI have been integrated into a single interface.

1.3 Ground Vehicle Component & Systems

Selection of a military relevant platform was a key decision that drove many aspects of our MAGIC 2010 entry. Based on currently deployed platforms, this meant the use of a tracked, skid-steer vehicle. The navigation would be more difficult than on a wheeled platform that can more heavily rely on wheel encoders. See Figure 4.

Terrain sensors added to the base platform includes a COTS LADAR configured in an innovative pattern and three fish eye cameras. The cameras are used for Object Of Interest (OOI) detection and tracking, visual odometry, and teleoperation when required. A custom made INU with GPS supply the core navigation solution. Two different radios provide a data link and a remote E-stop capability. A Core II duo processing board hosts the control system. A power distribution system allows hot swapping of batteries..

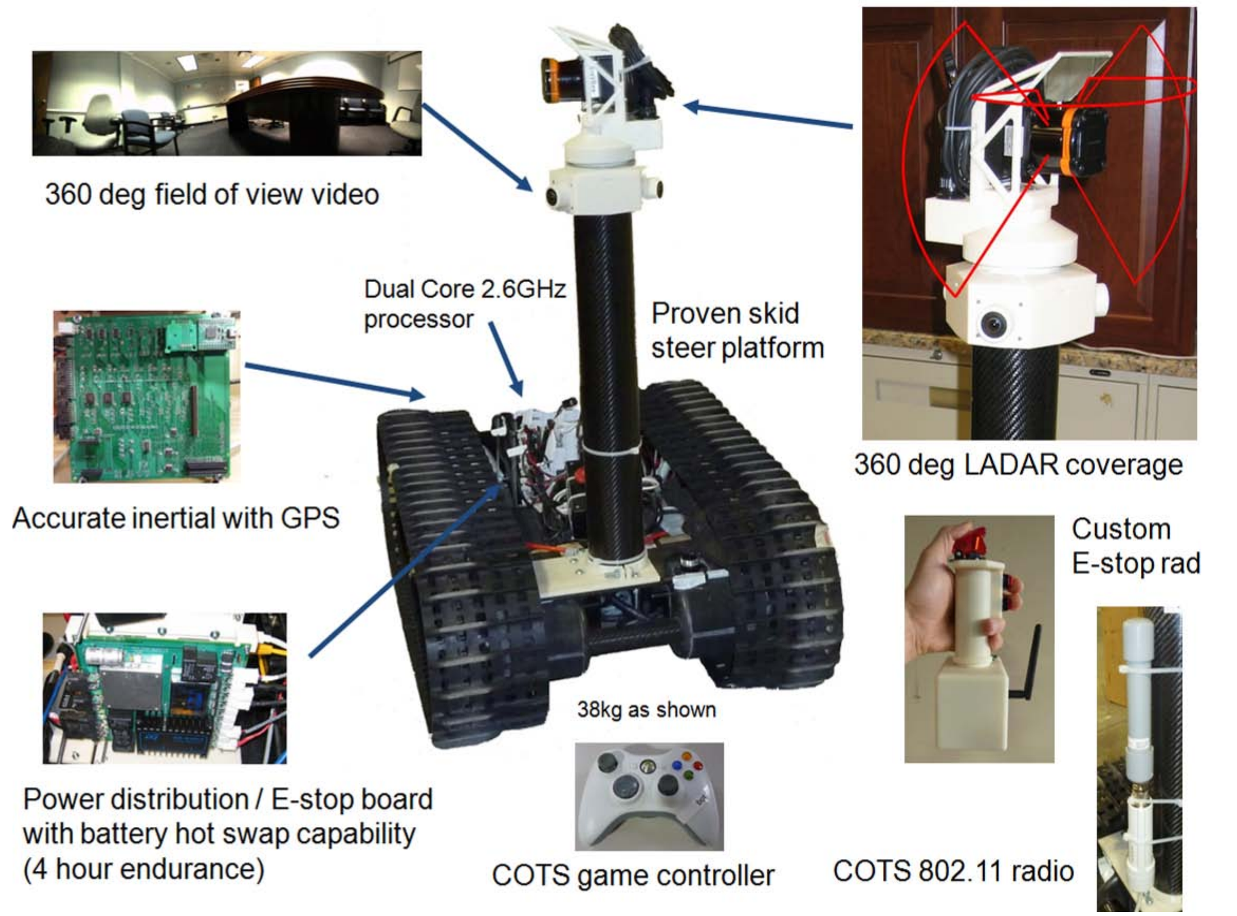

Figure 4 RASR-Bot detail

2. UVS Autonomy and Coordination Strategy

2.1 Introduction

MAGIC 2010 introduces a number of real world planning challenges:

- *Coordinating groups of vehicles is a highly dimensional search problem that cannot be fully expanded using realistic computational capabilities.*
- *Uncertainties of radio communication makes centralized approaches vulnerable to outages.*
- *Algorithmic cost spaces that include the opposing requirements of searching and neutralizing, create unbalanced search heuristics.*
- *Autonomous mobility in a small platform has stringent weight, power, and size constraints.*
- *A hybrid set of system capabilities from both a mission standpoint (sensor UGVs vs. disruptor UGVs), and from a computational standpoint (UGVs vs. OCUs).*
- *The need to perform localization and mapping indoors, without GPS.*

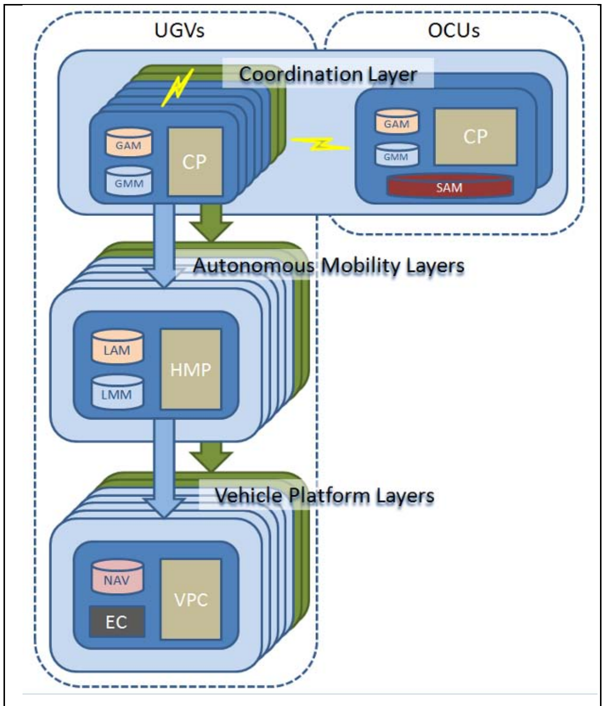

Figure 5 The control system is organized as a semi-distributed hierarchical architecture to minimize complexity while providing resiliency to communication outages.

The RASR approach unravels these challenges to provide a computationally feasible coordination and autonomous system that is highly resilient to communications and GPS outages.

2.2 Overall Planning and Coordination System

The planning and coordination system is hierarchically organized providing a distributed coordination layer and a group of specialized planners to solve the mapping and neutralization problems. Figure 5 shows the overall system diagram.

The system is organized so the elements at the top of the hierarchy are coarse, with slower planning cycles, while at the bottom of the hierarchy, the cycles are fast, and the resolution is high within a reduced scope. At the top of the hierarchy, the system has a coordination layer that plans the synchronized motion of the UGV group. It performs task allocation and rough scheduling of the group. This layer resides on each UGV as well as on the Operator Control Units. Each module in the layer is composed of a Coordination Planner (CP) which interacts with the Global Autonomous mobility Model (GAM) and the Global Mission Model (GMM). The OCU also contains a Situational Awareness Model (SAM). The Coordination Layer uses radio communications to maintain database coherency and to propagate plans.

Each vehicle has an Autonomous Mobility Layer (AM). AM is composed of a local version of a layered map and exposure database, the Local Autonomous mobility Model (LAM) and the Local Mission Model (LMM). The planner at this level solves the problem of single vehicle navigation and local coordination in the case of Neutralization. This layer receives coarse plans from the Coordination Layer, and provides plans that minimize local exposure and optimize mobility constraints for the UGV. These plans are sent to the Vehicle Platform Layer where the task is to transform these plans into actuator commands. The Vehicle Platform Layer maintains the navigation solution and provides the E-stop Controller (EC).

2.3 Representation

The system provides three concurrent representations:

The Autonomous Mobility World Model provides traversability information that is used by the different levels to calculate the costs of the plans from a mobility standpoint.

Mission Specific World Model provides information about the Object(s) of Interest (OOIs), and their motion prediction. It is represented in the form of a probability density function of each OOI being present at a location at a particular moment in time. The system will also maintain the exposure to OOIs (mobile or static) based on the mapped areas. A probability of detonation is computed using both layers.

Situational Awareness World Model is designed for operator consumption. This representation will allow the operator to understand the environment, and intervene if necessary.

2.4 Coordination Layer

The coordination layer resides on each UGV and on each OCU. Our overall philosophy embeds coordination capabilities on each robot in the architecture. The communications between robots is kept at a minimum by only propagating bounds of the solutions found in the nodes called “contracts.” When communications connect the UGVs and the OCUs; the coordination layer benefits from the larger number of computational units. In those cases, the larger number crunching capabilities of some nodes, like the OCUs, will provide search bounds to the rest of the robot team. When communications are poor and UGVs are isolated, they still can coordinate in their local communication neighborhood. It has been shown that this system is guaranteed to outperform an auctioning coordination strategy. The Robotic Research MPAC library (MPAC is software and system developed for autonomy of small unmanned surface vehicles) provides the search engine in the Coordination Layer Planner.

2.4.1 Generalized Formulation of Area Search

The search area is decomposed into a number of smaller areas called “countries”. Each country has a point, called the “capital”. From the capital, the robot can see every other point in the country. This depends on the range of the robot sensors and the line of sight around known obstacles. The creation of countries and capitals is described in the following section.

This generalized formulation allows other types of missions to be performed in addition to search-only missions. Additionally, the ability to plan for multiple types of vehicles is made possible by abstracting the tasks into the starting conditions, ending conditions, and resources required for completion. Through this basic formulation, a wide variety of pertinent missions can be managed on-the-fly by a group of UGVs.

2.4.2 K-Means Line of sight: KML

A new algorithm was designed to compute the countries and capitals. The idea behind KML is to find the smallest number of points (capitals) from which all the tiles in the desired search space can be viewed taking under consideration the line of sight. Once this is accomplished, the problem of coverage becomes a travelling salesman *without* having to do LOS checks or coverage propagation throughout the search. The space of search collapses by several (hundreds in most cases) orders of magnitude. See Figure 6. Some of the characteristics of KML:

- In the family of K-means, but guarantees LOS
- Minimizes number of points with similar convergence and warranties as K-means
- Minimizes the sums of squares. This is very important because it means that it computes paths that minimize distances to areas to be surveyed

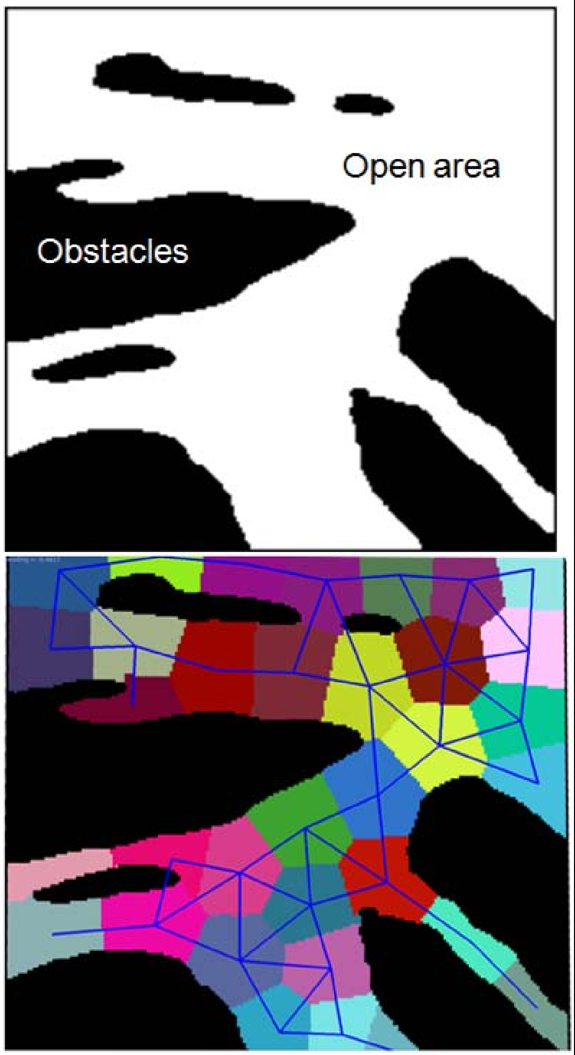

Figure 6. KML automatically subdivides the total area into smaller areas called "countries", each with a "capital". From the capital the robot can see the entire country, given the known obstacles.

- Efficient implementation

2.4.3 Anytime and Memory-Constrained Search Algorithms

All algorithms are designed to be "anytime algorithms." These algorithms can find solutions quickly (fast response) and will continue to improve solutions when given more time (ongoing improvement until the optimum solution is found). This approach also allows the algorithms to quickly respond and replan as new information is gathered, e.g. a new blockage is discovered. In addition, these algorithms have been designed, implemented, and tested to work within the memory available (from a single megabyte to multiple gigabytes). For sufficiently complex missions, the distributed algorithm will return a non-optimal plan immediately while continuing to improve the solution in the background.

Complementary to the anytime/memory aspects is the online optimality guarantees. By nature of the bounded search, a set of upper and lower bounds on the optimal solution are constantly being calculated. These bounds guarantee three important benefits: (1) the system is able to estimate how close the current solution is to the optimal solution as the search progresses, (2) the system is capable of proving it has found the optimal solution, and (3) the system is guaranteed to find the optimal solution when given sufficient computational resources.

2.4.4 Multi-Vehicle Coordination Algorithms

In a distributed environment, the propagation of information, the transfer of tasks, and communications topologies have been addressed. Robotic Research's "MPAC" system provides a contract-based multi-vehicle coordination system which provides an efficient way to share information and exchange task responsibilities even under degraded communications.

2.5 Path Planning at the Autonomous Mobility Layer

The autonomous mobility layer is based on the High Maneuverability Planner (HMP). This kino-dynamic planner has been utilized by U.S. Army unmanned platforms for a variety of programs including: the Collaborative Technology Alliance (U.S. Army Research Laboratory's (ARL) Robotics Collaborative Technology Alliance (RCTA)), Safe Ops (US Army, TARDEC, David Kowachek, PM), and the Autonomous Navigation System (PM FCS). The implementation on MAGIC is the first time it has been applied to small robots maneuvering in tight quarters.

This module generates trajectories for each UGV, avoiding obstacles while meeting the constraints of the plans created by the coordination layer. See Figure 7. An instance of this module resides on each UGV. The path planner's input is a 3D representation of its vicinity in a relative coordinate frame (LAM). It outputs a trajectory to be followed by the Vehicle Platform Layer (VPL). The HMP combines all sensor information into a single representation of the environment that is then utilized to evaluate the cost of performing different actions. As such, the environmental representation includes morphological information, as well as slippage characterization. The resulting trajectories are sequences of vehicle state/time pairs that the VPL follows. Among other things, the state information includes the desired vehicle position and attitude.

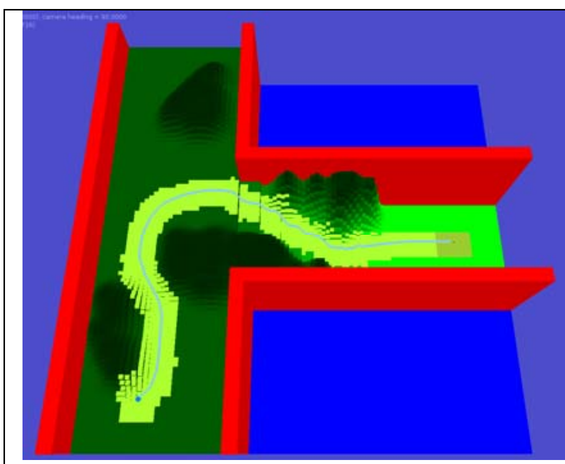

Figure 7 Simulation of the HMP generating a trajectory through a staircase with rubble. The HMP can handle both holonomic and non-holonomic platforms.

3. Sensors, Processing & Mapping for UGVs

Although sensing is not meant to be the core problem of the MAGIC 2010 challenge, several of the sensing requirements are not trivial. The system requires fusing LADAR and color vision to create maps and to Objects of Intrest. Robotic Research, Del Services, and GDRS have a long history of developing and testing sensing algorithms in robotic systems. Previous research allowed us to identify which areas needed work for the small UGVs. The sensing system fuses LADAR and color information to classify terrain, map the areas, and autonomously recognize and classify the static and dynamic OOIs. See Figure 8.

3.1 Sensor Processing

Static feature detection is performed by fusing morphological information provided by the LADAR together with color and texture information provided by the cameras. The most challenging aspect of the sensing requirements is the detection and prediction of movers. The team has shown this capability in many programs, for larger platforms (SafeOps and CTA) and smaller platforms (SBIR DARPA SB082-29 Multi-Sensor Detection and Tracking using Traversability Based Prediction, Dr. Robert Mandelbaum, PM.

3.2 Mapping Requirements

Three different models are maintained for different purposes: autonomy, mission tasks and Autonomous mobility Models (AM).

Two maps of the world are be maintained for mobility purposes; The Global Autonomous mobility Model (GAM) and the Local

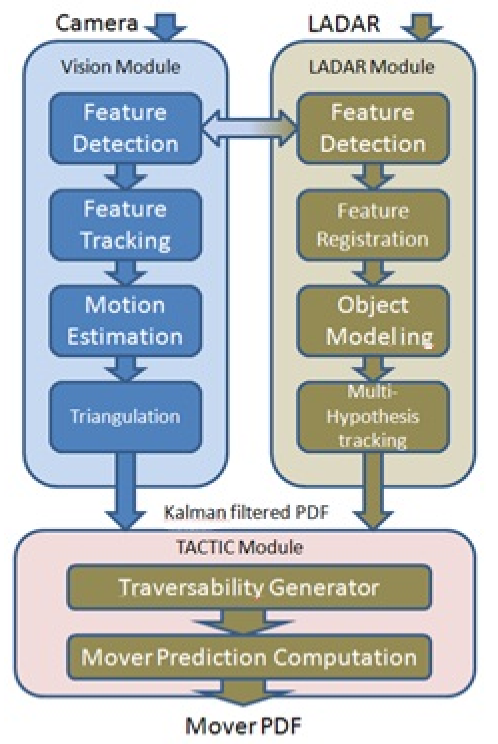

Figure 8 Sensor processing fuses video and LADAR information to sense, track and predict OOIs

Autonomous mobility Model (LAM). LAM is a vehicle centered grid based 2½ D map. Each tile in the map provides classification, elevation, density, and the presence of positive or negative obstacles.

Features in the LAM are used by the LADAR registration algorithms to merge all of the individual LAMs into a single coherent GAM. The GAM is displayed on the OCU.

3.3 Map Processing

The OCU has a model of the maps with the current best estimate of the vehicles navigation solution. As navigation information becomes available, including single robot loop closures and multi-robot loop closures, maps are regenerated from relative maps solutions. The resulting maps are then displayed on the OCU and used for generating the final map submission.

3.3.1 Mission Model (MM)

Since part of the mission is to correctly identify and neutralize OOIs, the MM is tasked with maintaining and predicting the knowledge about the humans. Dynamic OOIs are detected using onboard sensors and through the metadata provided by the UAV. Each vehicle tracks and classifies humans in its field of view and stores them in the Local MM (LMM), the Global MM is then used to maintain coherency of classification as the non-combatants and referees move in and out of the field of view of the UGVs. The MM at both levels also has the task of performing dynamic OOI prediction. In order to perform this prediction, the Terrain Aware Coordination Tool for Intelligent Control (TACTIC) is utilized. TACTIC was designed by Robotic Research for an Army War College challenge organized and funded by ARL in 2004. RR won this challenge by utilizing the TACTIC toolset.

TACTIC approximates the results of a Monte Carlo simulation at a much reduced computational burden. Figure 9 shows the motion prediction of TACTIC. In this simulation, a dynamic OOI starts at the far right. Based on its history, we assume that it is headed to the yellow line to the far left. The map has a series of mobility obstacles. Green areas represent predicted high probability areas, while red areas provide low probability areas.

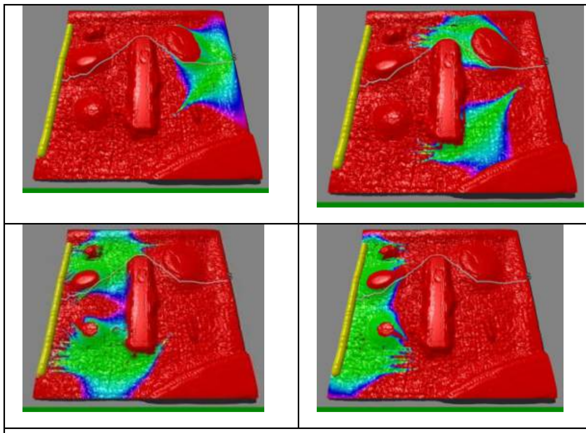

Figure 9 Mission module predicting the motion of a dynamic Object of Interest around a building.

In this case, the OOI is likely to walk north or south of the obstacle; however, the OOI is not likely to walk through it. This prediction is a probability density function (PDF) in (x,y,t). MM generates and maintains these PDFs. Based on the PDFs, and using the areas that have been previously explored, the MM provides information about the likelihood of finding a particular OOI in a particular location at a particular moment in time and, most importantly, the probability of entering in a death zone created by a dynamic OOI at a moment in time. By utilizing the GMM and by predicting the vehicle's own velocity, the planners at the coordination layer can plan to rendezvous with OOIs to initialize the neutralization procedures. At the autonomous mobility layer, this cost discourages entering rooms (without first clearing the entrance) as well as cutting corners around the buildings too sharply before first clearing the areas. It also provides guidance during the neutralization procedure so that a set of collaborating sensor UGVs are not cornered into situations that would force them to enter the kill zone of the dynamic OOI.

4. Operations in GPS-denied environments

The onboard navigation system is responsible for determining the pose of each robot, both the position (x, y, z) and orientation (roll, pitch, yaw). This system must work in buildings, near obstructions, and in the open.

Our team has extensive experience developing and using navigation systems for both robots and people. For the UGV we enhanced our existing adaptive Kalman filter with inputs from a 6 DOF MEMS IMU, wheel encoders, Differential GPS, visual odometry, and LADAR based map registration. See Figure 10. The result is a system that performs well indoors and outside and especially ensures a smooth transition between GPS and non-GPS environments.

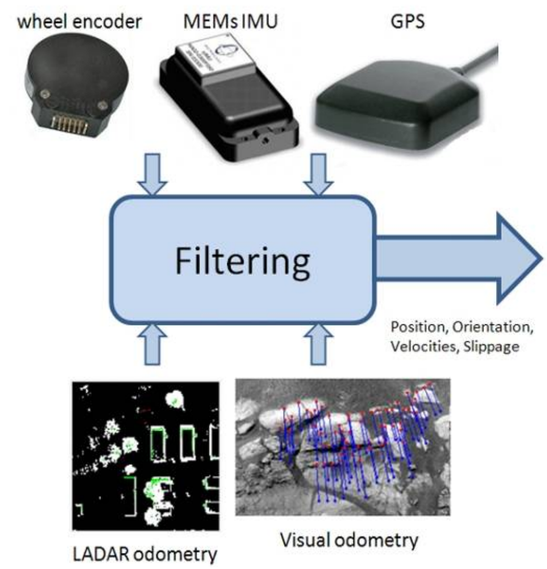

Figure 10 Pose estimation takes under consideration wheel encoders, MEMS IMU, GPS, LADAR odometry and visual odometry.

5. Human-machine interface (HMI)

5.1 Realtime Interaction

The Human Machine Interface (HMI) monitors and controls the three different levels of the system controller: the Platform, Autonomous Mobility, and the Coordination levels. The software is designed to be operated from a touch screen or from a more standard mouse and keyboard combination. The layout and organization is based on previous HMI designs and borrows aspects from online team video game strategies. See Figure 11.

The Coordination Layer HMI has been designed to aid the operator in viewing and modifying the coordination level plans. At this level the operator is not required to interact with individual trajectories of vehicles, but rather with coarse tasks and coarse scheduling decisions.

The Autonomous mobility HMI utilizes existing control methods: teleoperation, drive by waypoints, movable waypoints. RR and GD

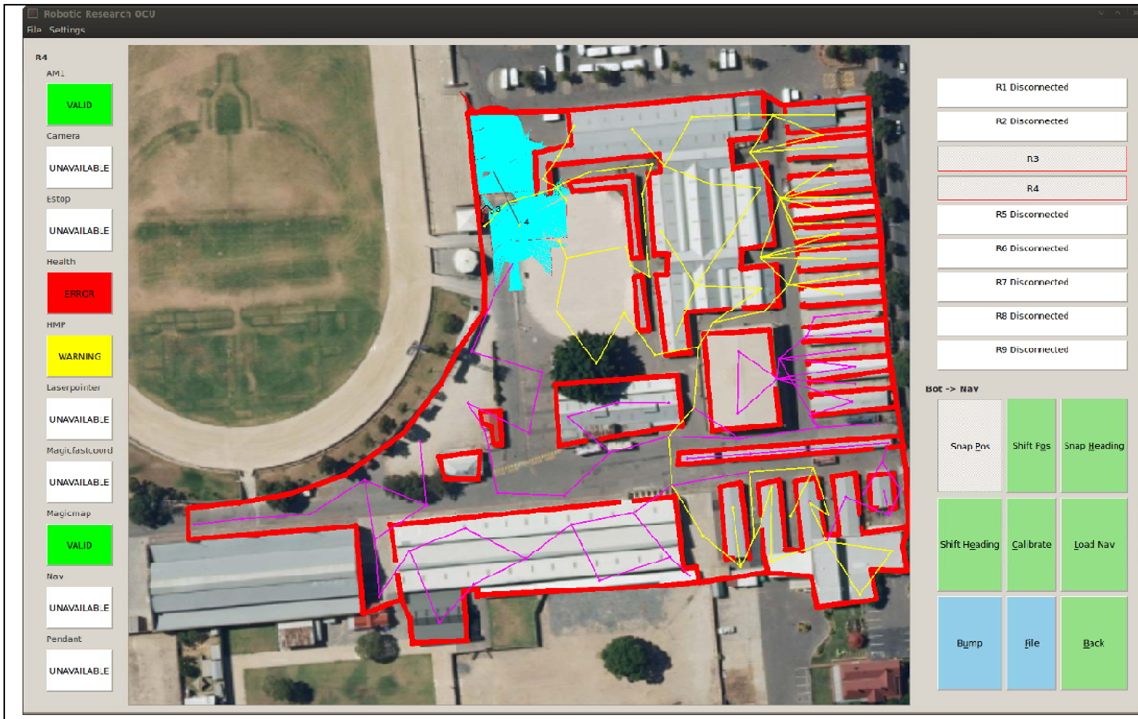

Figure 11. The HMI has been designed to provide efficient control from a keyboard or from a touch panel. It provides maps, area coverage, coordination and vehicle status.

previously developed and integrated these methods under the VTI program (VTI, POC Jillyn Alban TARDEC). The Neutralization HMIs provides two modalities. To neutralize a moving OOI, two video streams are shown to the operator for each UGV involved with the neutralization procedure. Results of dynamic OOI detection are framed so as to minimize operator burden.

The Platform HMI provides status of the different mechanical aspects of the UGVs and allows the operator to reboot subcomponents. This status is hierarchical, and additional information can be gleaned simply by touching the appropriate status symbol. Additionally, with warning and error states, commonly recommended operator actions are presented in a natural, seamless fashion.

5.2 After Action Capabilities

An After Action Review (AAR) toolkit was developed to provide the operator with information that he/she was not able to capture in real-time. RR-Viewer displays a virtual camera image geolocated with the generated map. As the robot traverses an area, the onboard cameras record the surroundings. The result is an enhanced viewing of the mission. The operator can change the pan, tilt, and zoom of the image and the software will generate the desired view from the omni-directional images collected onboard. It also displays the navigation solution from the vehicle as well as an optional 2D or 3D LADAR map display. See Figure 12.

6. Team Breakdown

Robotic Research, LLC - System integration, hardware and software design, navigation, video processing, autonomous mobility, multi-robot coordination, operator control station, testing, and configuration management.

Del Services - system integration, LADAR perception, autonomous mobility, and testing.

QinetiQ-NA (Parent company of Foster Miller and Applied Perception) - base platform, control and Symphony interface, shipping, Talon support in Australia.

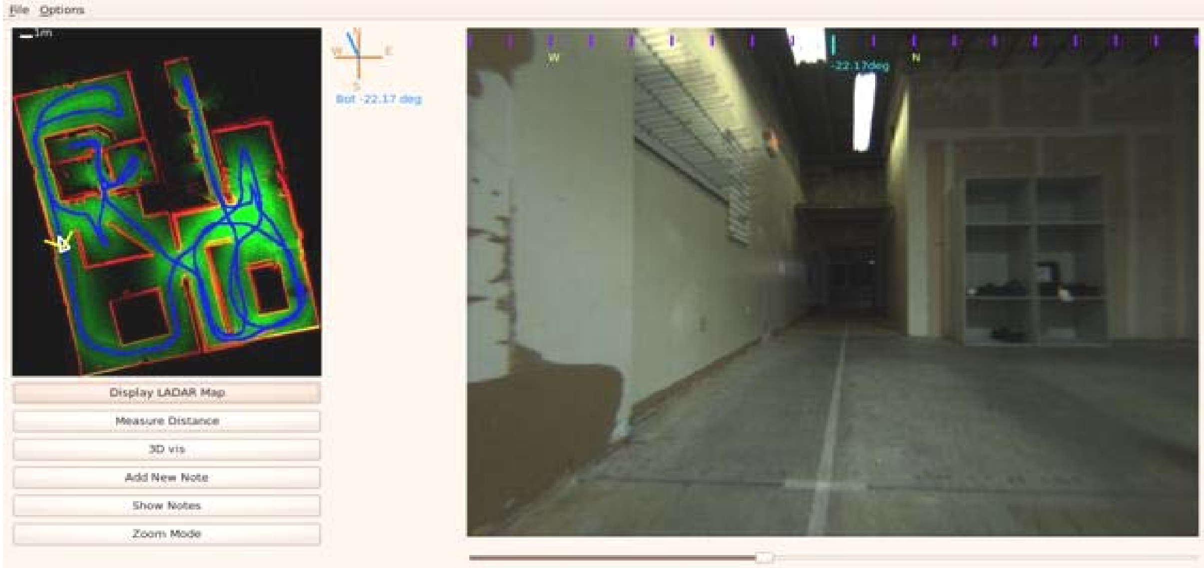

Figure 12. RR-Viewer allows the operator to pan, tilt, zoom and teleport to navigate the scene. 2D and 3 D maps are available as well image recall and playback from prior locations similar to Google's Streetview system.

General Dynamics Robotic Systems - enclosure design, part fabrication, business development support.

Cedar Creek Defense - communications.

Embry-Riddle Aeronautical University (ERAU) – hardware design trades, laser pointer mount design, system assembly, testing. Two ERAU interns worked at Robotic Research during the summer of 2010.

7. Summary

The RASR entry to the MAGIC 2010 competition provides robust autonomous mobility for small UGVs as well as an innovative coordination strategy capable of dealing with communication losses. The team took on the challenge of using a militarily relevant platform and a minimum set of relatively inexpensive navigation and LADAR sensors because this is the most likely pathway to deployment for the near-term benefit of the soldier.